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Curves of genus 2 with (N,N) decomposable Jacobians

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Abstract

Let C be a curve of genus 2 and $\psi_1 : C \longrightarrow E_1$ a map of degree n, from C to an elliptic curve E_1, both curves defined over $\mathbb{C}$. This map induces a degree n map $\phi_1 : \mathbb{P}^1 \longrightarrow \mathbb{P}^1$ which we call a Frey-Kani covering. We determine all possible ramifications for ϕ_1. If $\psi_1 : C \longrightarrow E_1$ is maximal then there exists a maximal map $\psi_2 : C \longrightarrow E_2$, of degree n, to some elliptic curve E_2 such that there is an isogeny of degree n^2 from the Jacobian J_C to $E_1 \times E_2$. We say that J_C is (n, n)-decomposable. If the degree n is odd the pair (ψ_2, E_2) is canonically determined. For $n = 3$, 5, and 7, we give arithmetic examples of curves whose Jacobians are (n, n)-decomposable.

1. Introduction

Curves of genus 2 with non-simple Jacobians are of much interest. Their Jacobians have large torsion subgroups, e.g. Howe, Leprévost, and Poonen have found a family of genus 2 curve with 128 rational points in its Jacobian, see (5). For other applications of genus 2 curves with (n, n)-decomposable Jacobians see Frey (2). In this paper, we discuss genus 2 curves C whose function fields have maximal elliptic subfields. These elliptic subfields occur in pairs (E_1, E_2) and we call each the complement of the other in J_C. The Jacobian of C is isogenous to $E_1 \times E_2$. Let $\psi : C \to E$ be a maximal cover (cf. section 4) of odd degree n. The moduli space parameterizing these covers is a surface, more precisely the product of modular curves $X(n) \times X(n)/\Delta$, see Kani (6). When $\psi : C \to E$ is degenerate (cf. section 2), this moduli space is a curve. Getting algebraic descriptions for these spaces is extremely difficult for large n (e.g. $n \geq 7$). Also, one would like to know how the elements of the pair (E_1, E_2) relate to each other.

In sections 2 and 3 we define a Frey-Kani covering and determine all their possible ramifications. In section 4 we consider maximal covers. These covers allow us to determine the complement of E_1 uniquely. The last section deals with some applications when $n = 3, 5$, or 7.

2. Frey - Kani covers

Let C and E be curves of genus 2 and 1, respectively. Both are smooth, projective curves defined over $\mathbb{C}$. Let $\psi : C \longrightarrow E$ be a covering of degree n. We say that E is an degree n *elliptic subcover* of C. From the Riemann-Hurwitz formula, $\sum_{P\in C}(e_\psi(P)-1)=2$ where $e_\psi(P)$ is the ramification index of points $P \in C$, under ψ. Thus, we have two points of ramification index 2 or one point of ramification index 3. The two points of ramification index 2 can be in the same fiber or in different fibers. Therefore, we have the following cases of the covering ψ:

Case I. There are $P_1,\ P_2 \in C$, such that $e_\psi(P_1)=e_\psi(P_2)=2$, $\psi(P_1)\neq\psi(P_2)$, and $\forall P \in C\setminus\{P_1,P_2\}$, $e_\psi(P)=1$.

Case II. There are $P_1,\ P_2 \in C$, such that $e_\psi(P_1)=e_\psi(P_2)=2$, $\psi(P_1)=\psi(P_2)$, and $\forall P \in C\setminus\{P_1,P_2\}$, $e_\psi(P)=1$.

Case III. There is $P_1 \in C$ such that $e_\psi(P_1)=3$, and $\forall P\in C\setminus\{P_1\}$, $e_\psi(P)=1$

In case I (resp. II, III) the cover ψ has 2 (resp. 1) branch points in E.

Denote the hyperelliptic involution of C by w. We choose $\mathcal{O}$ in E such that w restricted to E is the hyperelliptic involution on E, see (3) or (7). We denote the restriction of w on E by v, $v(P)=-P$. Thus, $\psi\circ w = v\circ\psi$. E[2] denotes the group of 2-torsion points of the elliptic curve E, which are the points fixed by v. The proof of the following two lemmas is straightforward and will be omitted.

Lemma 2.1: *a) If $Q\in E$, then $\forall P\in\psi^{-1}(Q)$, $w(P)\in\psi^{-1}(-Q)$.*
b) For all $P\in C$, $e_\psi(P)=e_\psi(w(P))$.

Let W be the set of points in C fixed by w. Every curve of genus 2 is given, up to isomorphism, by a binary sextic, so there are 6 points fixed by the hyperelliptic involution w, namely the Weierstrass points of C. The following lemma determines the distribution of the Weierstrass points in fibers of 2-torsion points.

Lemma 2.2: *1. $\psi(W)\subset E[2]$*

2. If n is an odd number then
- *i) $\psi(W)=E[2]$*
- *ii) If $Q\in E[2]$ then $\#(\psi^{-1}(Q)\cap W)=1 \mod (2)$*

3. If n is an even number then for all $Q\in E[2]$, $\#(\psi^{-1}(Q)\cap W)=0 \mod (2)$

Let $\pi_C : C\longrightarrow\mathbb{P}^1$ and $\pi_E : E\longrightarrow\mathbb{P}^1$ be the natural degree 2 projections. The hyperelliptic involution permutes the points in the fibers of π_C and π_E. The ramified points of π_C, π_E are respectively points in W and $E[2]$ and their ramification index is 2. There is $\phi : \mathbb{P}^1\longrightarrow\mathbb{P}^1$ such that the diagram commutes, see Frey (3) or Kuhn (7).

$$\begin{array}{ccc} C & \xrightarrow{\pi_C} & \mathbb{P}^1 \\ \psi\downarrow & & \downarrow\phi \\ E & \xrightarrow{\pi_E} & \mathbb{P}^1 \end{array}$$

The covering $\phi : \mathbb{P}^1\longrightarrow\mathbb{P}^1$ will be called the corresponding **Frey-Kani covering** of $\psi : C\longrightarrow E$. It has first appeared in (3) and (2). The term, Frey-Kani covering, has first been used by Fried in (4).

3. The ramification of Frey-Kani coverings

In this section we will determine the ramification of Frey-Kani coverings $\phi : \mathbb{P}^1 \longrightarrow \mathbb{P}^1$. First we fix some notation. For a given branch point we will denote the ramification of points in its fiber as follows. Any point P of ramification index m is denoted by (m). If there are k such points then we write $(m)^k$. We omit writing symbols for unramified points, in other words $(1)^k$ will not be written. Ramification data between two branch points will be separated by commas. We denote by $\pi_E(E[2]) = \{q_1, \dots, q_4\}$ and $\pi_C(W) = \{w_1, \dots, w_6\}$.

3.1. The case when n is odd

The following theorem classifies the ramification types for the Frey-Kani coverings $\phi : \mathbb{P}^1 \longrightarrow \mathbb{P}^1$ when the degree n is odd.

THEOREM 3.1: *If $\psi : C \longrightarrow E$ is a covering of odd degree n then the three cases of ramification for ψ induce the following cases for $\phi : \mathbb{P}^1 \longrightarrow \mathbb{P}^1$.*

Case I: *(the generic case)*

$$\left((2)^{\frac{n-1}{2}}, (2)^{\frac{n-1}{2}}, (2)^{\frac{n-1}{2}}, (2)^{\frac{n-3}{2}}, (2)^1\right)$$

Or the following degenerate cases:

Case II: *(the 4-cycle case and the dihedral case)*

i) $\left((2)^{\frac{n-1}{2}}, (2)^{\frac{n-1}{2}}, (2)^{\frac{n-1}{2}}, (4)^1(2)^{\frac{n-7}{2}}\right)$

ii) $\left((2)^{\frac{n-1}{2}}, (2)^{\frac{n-1}{2}}, (2)^{\frac{n-1}{2}}, (2)^{\frac{n-1}{2}}\right)$

iii) $\left((2)^{\frac{n-1}{2}}, (2)^{\frac{n-1}{2}}, (4)^1(2)^{\frac{n-5}{2}}, (2)^{\frac{n-3}{2}}\right)$

Case III: *(the 3-cycle case)*

i) $\left((2)^{\frac{n-1}{2}}, (2)^{\frac{n-1}{2}}, (2)^{\frac{n-1}{2}}, (3)^1(2)^{\frac{n-5}{2}}\right)$

ii) $\left((2)^{\frac{n-1}{2}}, (2)^{\frac{n-1}{2}}, (3)^1(2)^{\frac{n-3}{2}}, (2)^{\frac{n-3}{2}}\right)$

Proof: From lemma 2.2 we can assume that $\phi(w_i) = q_i$ for $i \in \{1, 2, 3\}$ and $\phi(w_4) = \phi(w_5) = \phi(w_6) = q_4$. Next we consider the three cases for the ramification of $\psi : C \longrightarrow E$ and see what ramifications they induce on $\phi : \mathbb{P}^1 \longrightarrow \mathbb{P}^1$.

Suppose that $P \in \psi^{-1}(E[2]) \setminus W$ and $e_\psi(P) = 1$. Then $e_\psi(P) \cdot e_{\pi_E}(\psi(P)) = e_{\pi_C}(P) \cdot e_\phi(\pi_C(P)) = 2$, so $e_\phi(\pi_C(P)) = 2$.

Case I: There are P_1 and P_2 in C such that $e_\psi(P_1) = e_\psi(P_2) = 2$ and $\psi(P_1) \neq \psi(P_2)$. By lemma 2.1, $e_\psi(w(P_1)) = 2$. So $w(P_1) = P_1$ or $w(P_1) = P_2$.

Suppose that $w(P_1) = P_1$, so $P_1 \in W$. If $\pi_C(P_1) = w_i$ for $i \in \{1, 2, 3\}$, say $\pi_C(P_1) = w_1$, then $e_{\pi_E \circ \psi}(P_1) = e_{\phi \circ \pi_C}(P_1) = 4$, which implies that $e_\phi(w_1) = 2$. All other points in the fiber of $\pi_E \circ \psi(P_1) =: q_1$ have ramification index 2 under ϕ. So ϕ has even degree, which is a contradiction. If $\pi_C(P_1) = w_i$ for $i \in \{4, 5, 6\}$, say $\pi_C(P_1) = w_4$, then in the fiber of q_4 are: w_4 of ramification index 2, w_5 and w_6 unramified, and all other points have ramification index 2.

So $\#(\phi^{-1}(q_4)) = 2+1+1+2k$, is even. Thus $P_1, P_2 \notin W$. Then $P_1, P_2 \notin \psi^{-1}(E[2])$, otherwise they would be in the same fiber.

Thus $P_2 = w(P_1) \in C \setminus \psi^{-1}(E[2])$ and $\psi(P_1) = -\psi(P_2)$. Let $\pi_E \circ \psi(P_1) = \pi_E \circ \psi(P_2) = q_5$ and $\pi_C(P_1) = \pi_C(P_2) = S$. So $e_\psi(P_1) \cdot e_{\pi_E}(\psi(P_1)) = e_{\pi_C}(P_1) \cdot e_\phi(\pi_C(P_1))$. Thus, $e_\phi(\pi_C(P_1)) = e_\phi(S) = 2$. All other points in $\phi^{-1}(q_5)$ are unramified.

For $P \in W$, $e_{\pi_C}(P) = 2$. Thus $e_\phi(\pi_C(P)) = 1$. All $w_1, \ldots w_6$ are unramified and other points in $\phi^{-1}(E[2])$ are of ramification index 2. By the Riemann - Hurwitz formula, ϕ is unramified everywhere else.

Thus, there are $\frac{n-1}{2}$ points of ramification index 2 in the fibers $\phi^{-1}(q_1)$, $\phi^{-1}(q_2)$, $\phi^{-1}(q_3)$, $\frac{n-3}{2}$ points of ramification index 2 in $\phi^{-1}(q_4)$, and one point of index 2 in $\phi^{-1}(q_5)$.

Case II: In this case, there are distinct P_1 and P_2 in C such that $e_\psi(P_1) = e_\psi(P_2) = 2$ and $\psi(P_1) = \psi(P_2)$. Then $P_2 = w(P_1)$ or $w(P_i) = P_i$, for $i = 1, 2$.

Let P_1 and P_2 be in the fiber which has three Weierstrass points.

i) Suppose that w permutes P_1 and P_2. So P_1 and P_2 are not Weierstrass points. Then $e_{\pi_E \circ \psi}(P_1) = e_\psi(P_1) \cdot e_{\pi_E}(\psi(P_1)) = 4$. Thus $e_{\pi_C}(P_1) \cdot e_\phi(\pi_C(P_1)) = 4$. Since $e_{\pi_C}(P_1) = 1$ then $e_\phi(\pi_C(P_1) = 4$. So there is a point of index 4 in the fiber of q_4. The rest of the points are of ramification index 2, as in previous case, other then the $w_1, \ldots, w_6$ which are unramified.

ii) Suppose that w fixes P_1 and P_2. Thus P_1 and P_2 are Weierstrass points. Then $e_\psi(P_i) \cdot e_{\pi_E}(\psi(P_i)) = e_{\pi_C}(P_i) \cdot e_\phi(\pi_C(P_i)) = 4$. So $e_\phi(\pi_C(P_i)) = 2$. Thus, $\pi_C(P_i)$ have ramification index 2. The other points behave as in the previous case. So we have in each fiber of ϕ one unramified point and everything else has ramification index 2.

Suppose that P_1 and P_2 are in one of the fibers which have only one Weierstrass point.

iii) Then w has to permute them, so they are not Weierstrass points. As in case i) $e_\phi(\pi_C(P_1)) = 4$. So there is a point of index 4 in one of $\psi^{-1}(q_1)$, $\psi^{-1}(q_2)$,$\psi^{-1}(q_3)$ and everything else is of ramification index 2. The Weierstrass points are as in case i), unramified.

Case III: Let P be the ramified point of index 3. By lemma 1, $e_\psi\, w(P) = 3$. But there is only one such point in C, so $P \in W$. Then $e_{\pi_E \circ \psi}(P) = e_\psi(P) \cdot e_{\pi_E}(\psi(P)) = 6$. So $e_{\pi_C}(P) \cdot e_\phi(\pi_C(P)) = 6$. But $e_{\pi_C}(P) = 2$, because $P \in W$. Thus, $e_\phi(\pi_C(P)) = 3$.

i) Q is in the fiber that contains three Weierstrass points. Then we have a point of ramification index three in $\psi^{-1}(q_4)$, two other Weierstrass points are unramified, and all the other points are of ramification index 2.

ii) Q is in one of the fibers that contains only one Weierstrass point. Then in one of $\psi^{-1}(q_1)$, $\psi^{-1}(q_2)$, $\psi^{-1}(q_2)$ there is a point of index 3 and everything else is of index 2. $\square$

3.2. The case when n is even

Let us assume now that $deg(\psi) = n$ is an even number. The following theorem classifies the Frey-Kani coverings in this case.

THEOREM 3.2: *If n is an even number then the generic case for $\psi : C \longrightarrow E$ induce the following three cases for $\phi : \mathbb{P}^1 \longrightarrow \mathbb{P}^1$:*

I. $\left((2)^{\frac{n-2}{2}}, (2)^{\frac{n-2}{2}}, (2)^{\frac{n-2}{2}}, (2)^{\frac{n}{2}}, (2)\right)$

II. $\left((2)^{\frac{n-4}{2}}, (2)^{\frac{n-2}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}, (2)\right)$

III. $\left((2)^{\frac{n-6}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}, (2)\right)$

Each of the above cases has the following degenerations (two of the branch points collapse to one)

I. *1.* $\left((2)^{\frac{n}{2}}, (2)^{\frac{n-2}{2}}, (2)^{\frac{n-2}{2}}, (2)^{\frac{n}{2}}\right)$

2. $\left((2)^{\frac{n-2}{2}}, (2)^{\frac{n-2}{2}}, (4)(2)^{\frac{n-6}{2}}, (2)^{\frac{n}{2}}\right)$

3. $\left((2)^{\frac{n-2}{2}}, (2)^{\frac{n-2}{2}}, (2)^{\frac{n-2}{2}}, (4)(2)^{\frac{n-4}{2}}\right)$

4. $\left((3)(2)^{\frac{n-4}{2}}, (2)^{\frac{n-2}{2}}, (2)^{\frac{n-2}{2}}, (2)^{\frac{n}{2}}\right)$

II. *1.* $\left((2)^{\frac{n-2}{2}}, (2)^{\frac{n-2}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}\right)$

2. $\left((2)^{\frac{n-4}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}\right)$

3. $\left((4)(2)^{\frac{n-8}{2}}, (2)^{\frac{n-2}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}\right)$

4. $\left((2)^{\frac{n-4}{2}}, (4)(2)^{\frac{n-6}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}\right)$

5. $\left((2)^{\frac{n-4}{2}}, (2)^{\frac{n-2}{2}}, (2)^{\frac{n-4}{2}}, (2)^{\frac{n}{2}}\right)$

6. $\left((3)(2)^{\frac{n-6}{2}}, (2)^{\frac{n-2}{2}}, (4)(2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}\right)$

7. $\left((2)^{\frac{n-4}{2}}, (3)(2)^{\frac{n-4}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}\right)$

III. *1.* $\left((2)^{\frac{n-4}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}, (4)(2)^{\frac{n}{2}}\right)$

2. $\left((2)^{\frac{n-6}{2}}, (4)(2)^{\frac{n-4}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}\right)$

3. $\left((2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}, (4)(2)^{\frac{n-10}{2}}\right)$

4. $\left((3)(2)^{\frac{n-8}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}, (2)^{\frac{n}{2}}\right)$

Proof: We know that the number of Weierstrass points in the fibers of 2-torsion points is 0 mod (2). Combining this with the Riemann - Hurwitz formula we get the three cases of the general case.

To determine the degenerate cases we consider cases when there is one branch point for $\psi : C \longrightarrow E$.

I) First, assume that the branch point has two points P_1 and P_2 of index 2 (Case II). Then $w(P_1) = P_i$ for $i = 1, 2$ or $w(P_1) = P_2$. The first case implies that $P_1, P_2 \in W$. Then $e_\phi(w(P_1)) = e_\phi(w(P_2)) = 2$. So we have case I, 1. When $w(P_1) = P_2$ then $e_\phi(w(P_1)) = 4$. Thus, we have a point of index 4 in $\phi^{-1}(q)$ for $q \in \{q_1, \dots, q_4\}$. Therefore cases 2 and 3. If there is $P \in C$ such that $e_\psi(P) = 3$, then $P \in W$ and $e_\phi(w(P)) = 3$. So we have case 4.

II) As in case I, if P_1 and P_2 are Weierstrass points then they can be in the fiber of the point which has 4 or 2 Weierstrass points. So we get two cases, namely 1 and 2. Suppose now that P_1 and P_2 are not Weierstrass points, thus $w(P_1) = P_2$ and $e_\phi(w(P_1)) = 4$. This point

of index 4 can be in the same fiber with 4, 2 or none Weierstrass points. So we get cases 3, 4, and 5 respectively. A point of index 3 is a Weierstrass point which can be in the fiber which has 4 or 2 Weierstrass points. So cases 6 and 7.

III) If P_1 and P_2 are Weierstrass points then they can be only in the fiber with 6 Weierstrass point so case 1. If they are not then we have a point of index 4 which can be in the fiber with all Weierstrass points or with none. Therefore, cases 2 and 3. The point of index 3 is a Weierstrass point so it can be in the fiber where all the Weierstrass points are, so case 4. This completes the proof. □

4. Maximal coverings $\psi : C \longrightarrow E$.

Let $\psi_1 : C \longrightarrow E_1$ be a covering of degree n from a curve of genus 2 to an elliptic curve. The covering $\psi_1 : C \longrightarrow E_1$ is called a **maximal covering** if it does not factor over a nontrivial isogeny. A map of algebraic curves $f : X \to Y$ induces maps between their Jacobians $f^* : J_Y \to J_X$ and $f_* : J_X \to J_Y$. When f is maximal then f^* is injective and $ker(f_*)$ is connected, see (9) (p. 158) for details.

Let $\psi_1 : C \longrightarrow E_1$ be a covering as above which is maximal. Then ${\psi^*}_1 : E_1 \to J_C$ is injective and the kernel of $\psi_{1,*} : J_C \to E_1$ is an elliptic curve which we denote by E_2, see (3) or (7). For a fixed Weierstrass point $P \in C$, we can embed C to its Jacobian via

$$i_P : C \longrightarrow J_C$$

$$x \to [(x) - (P)]$$

Let $g : E_2 \to J_C$ be the natural embedding of E_2 in J_C, then there exists $g_* : J_C \to E_2$. Define $\psi_2 = g_* \circ i_P : C \to E_2$. So we have the following exact sequence

$$0 \to E_2 \xrightarrow{g} J_C \xrightarrow{\psi_{1,*}} E_1 \to 0$$

The dual sequence is also exact, see (3)

$$0 \to E_1 \xrightarrow{\psi_1^*} J_C \xrightarrow{g_*} E_2 \to 0$$

The following lemma shows that ψ_2 has the same degree as ψ_1 and is maximal.

Lemma 4.1: *a) $deg\,(\psi_2) = n$*
b) ψ_2 is maximal

Proof: For every $D \in Div\,(E_2)$, $deg\,(\psi_2^* D) = deg\,(\psi_2) \cdot deg\,(D)$. Take $D = \mathcal{O}_2 \in E_2$, then $deg\,(\psi_2^*\, \mathcal{O}_2) = deg\,(\psi_2)$. Also $\psi_2^*\,(\mathcal{O}_2) = (\psi_2^*\, \mathcal{O}_2)$ as divisor and

$$\psi_2^*\, \mathcal{O}_2 = i_P^*\, g(\mathcal{O}_2) = i_P^*\, \mathcal{O}_J = \psi_1^*\, \mathcal{O}_1$$

So $deg\,(\psi_2^*\, \mathcal{O}_2) = deg\,(\psi_1^*\, \mathcal{O}_1) = deg\,(\psi_1) = n$

To prove the second part suppose $\psi_2 : C \longrightarrow E_2$ is not maximal. So there exists an elliptic curve E_0 and morphisms ψ_0 and β, such that the following diagram commutes

$$\begin{tikzcd} C \arrow[d, "\psi_0"'] \arrow[dr, "\psi_2"] & \\ E_0 \arrow[r, "\beta"] & E_2 \end{tikzcd}$$

Take $\psi_0(P)$ to be the identity of E_0. Then exists $\psi_{0*} : J_C \longrightarrow E_0$ such that $\psi_0 = \psi_{0*} \circ i_P$. Thus, $\psi_{2,*} = \beta \circ \psi_{0,*}$. So $ker\, \psi_{0,*}$ is a proper subgroup of $ker\, \psi_{2,*} = E_1$, since $deg\, \beta > 1$. Thus,

$$\psi_{0,*}|_{E_1} : E_1 \longrightarrow ker\, \beta$$

is a surjective homomorphism. Therefore, E_1 has a proper subgroup of finite index. So, there exists an intermediate field between function fields $\mathbb{C}(C)$ and $\mathbb{C}(E_1)$. This contradicts the fact that ψ_1 is maximal $\square$

If $deg(\psi_1)$ is an odd number then the maximal covering $\psi_2 : C \to E_2$ is unique (up to isomorphism of elliptic curves), see Kuhn (7).

To each of the covers $\psi_i : C \longrightarrow E_i$, $i = 1, 2$, correspond Frey-Kani covers $\phi_i : \mathbb{P}^1 \longrightarrow \mathbb{P}^1$. If the cover $\psi_1 : C \longrightarrow E_1$ is given, and therefore ϕ_1, we want to determine $\psi_2 : C \longrightarrow E_2$ and ϕ_2. The study of the relation between the ramification structures of ϕ_1 and ϕ_2 provides information in this direction. The following lemma (see (3), p. 160) answers this question for the set of Weierstrass points $W = \{P_1, \dots, P_6\}$ of C when the degree of the cover is odd.

Let $\psi_i : C \longrightarrow E_i$, $i = 1, 2$, be maximal of odd degree n. Let $\mathcal{O}_i \in E_i[2]$ be the points which has three Weierstrass points in its fiber. Then we have the following:

Lemma 4.2 (Frey-Kani): *The sets $\psi_1^{-1}(\mathcal{O}_1) \cap W$ and $\psi_2^{-1}(\mathcal{O}_2) \cap W$ form a disjoint union of W.*

When n is even the ramification of ψ, is more precise.

Lemma 4.3: *Let $\psi : C \longrightarrow E$ is maximal of even degree n, and $Q \in E[2]$. Then $\psi^{-1}(Q)$ has either none or two Weierstrass points.*

Proof: If there are no Weierstrass points in $\psi^{-1}(Q)$ there is nothing to prove. Suppose there is one, from lemma 3.2 we know there are at least 2, say P_1, P_2. We embed $C \hookrightarrow J_C$ via $x \longrightarrow [(x) - (P_1)]$ and $E \longrightarrow J_E$ via $x \longrightarrow [(x) - (Q)]$.

$$\begin{array}{ccc} C & \xrightarrow{i_{P_1}} & J_C \\ \psi \downarrow & & \downarrow \psi_* \\ E & \xrightarrow{i_Q} & J_E \end{array}$$

Then $\psi_*([(x) - (P_1)]) = [(\psi(x)) - (Q)]$.

Also, $\psi_* \psi^* = [n]$ is the multiplication by n in E. Since $2|n$ then $E[2]$ is a subgroup of $E[n]$. So $\psi^*(E[2]) = ker(\psi_*|_{J[2]})$, we call this group H. Suppose $P_3 \in \psi^{-1}(Q)$. Then $\psi_*(i_{P_1}(P_3)) = \mathcal{O}_E$, so $(P_1, P_3) \in H$, where the unordered pair (P_i, P_j) denotes the point $[(P_i) - (P_j)]$ of order 2 in J_C. By addition of points of order 2 in J_C, $(P_2, P_3) \in H$. So

$H = \{0_J, (P_1, P_2), (P_1, P_3), (P_2, P_3)\}$ can't have any other points, therefore $\psi^{-1}(Q)$ has three Weierstrass points, which contradicts theorem 3.2. Thus, there are only two Weierstrass points in $\psi^{-1}(Q)$. $\square$

The above lemma says that if ψ is maximal of even degree then the corresponding Frey-Kani covering can have only type **I** ramification, see theorem 3.1.

5. Arithmetic Applications

In this section, we characterize genus 2 curves with degree 3 elliptic subcovers and determine the j-invariants of these elliptic subcovers in terms of coefficients of the genus 2 curve. If the elliptic subcover is of degenerate ramification type, then its j-invariant is determined in terms of the absolute invariants of the genus 2 curve. We find two isomorphism classes of genus 2 curves which have both elliptic subcovers of degenerate type.

When $n = 5$ or 7 we discuss only Case II, iii), and Case II, i) of theorem 3.1, respectively. In both cases we determine the j-invariants of elliptic subcovers in terms of the coefficients of the genus 2 curves. Other types of ramifications are computationally harder and results are very large for display.

5.1. Curves of genus 2 with a degree 3 elliptic subfield.

Let $\psi : C \to E_1$ be a covering of degree 3, where C is a genus 2 curve given by

$$C : Y^2 = x(x-1)(x-d)(x^3 - ax^2 + bx - c)$$

and E_1 an elliptic curve. Denote the 2-torsion points of E_1 by $0, 1, t, s$. Let ϕ_1 be the Frey-Kani covering with $deg\,(\phi_1) = 3$ such that $\phi_1\,(0) = 0$, $\phi_1\,(1) = 1$, $\phi_1\,(d) = t$, and the roots of $f(x) = x^3 - ax^2 + bx - c$, are in the fiber of s. The fifth branch point is infinity and in its fiber is u of index 1 and infinity of index 2. So ϕ_1 is of generic type (Theorem 3.1). Points of index 2 in the fibers of 0, 1, t are m, n, p respectively. Then the cover is given by

$$z = k\frac{x(x-m)^2}{x-u}$$

Then from equations:

$$z - 1 = k(x-1)(x-n)^2, \quad z - t = k(x-d)(x-p)^2, \quad z - s = f(x)$$

we compare the coefficients of x and get a system of 9 equations in the variables $a, b, c, d, k, m, n, p, t, s, u$. Using the Buchberger's Algorithm (see (1), p. 86-91) and a computational symbolic package (as Maple) we get;

Lemma 5.1: *Let E_1 be the elliptic curve given by $y^2 = z(z-1)(z-t)(z-s)$. Then the genus 2 curve*

$$C : Y^2 = x(x-1)\left(x - \frac{a(a-2)}{2a-3}\right)\left(x^3 - ax^2 + \left(\frac{(2a-3)c}{(a-1)^2} + \frac{a^2}{4}\right)x - c\right)$$

covers E_1 with a maximal cover of degree 3 of generic case (Theorem 3.1). Moreover s and t are given by,

$$t = \frac{a^3(a-2)}{(2a-3)^3}, \quad s = \frac{4c}{(a-1)^2}$$

□

Next, we find the j-invariants of E_1 and E_2. The j-invariant of E_1 is as follows,

$$j(E_1) = \frac{16}{C^2} \cdot \frac{A^3}{a^6c^2(a-1)^2(a-2)^2(a-3)^6\left((a-1)^2-4c\right)^2}$$

where A and C are:

$$\begin{aligned} A =& a^{12} - 8a^{11} + 16c^2a^8 + 11664c^2 + 36720c^2a^4 - 69984c^2a^3 - 192c^2a^7 + 77760c^2a^2 \\ &- 46656c^2a + 1920c^2a^6 - 11232c^2a^5 - 4a^{10}c + 26a^{10} - 44a^9 + 41a^8 - 20a^7 + 220a^8c \\ &- 904a^7c + 1740a^6c - 1800a^5c - 8a^9c - 216ca^3 + 4a^6 + 972ca^4 \\ C =& a^6 - 4a^5 + 5a^4 - 2a^3 - 32a^3c + 144ca^2 - 216ca + 108c \end{aligned} \tag{1}$$

To find j_2 we take $\phi_2 : \mathbb{P}^1 \to \mathbb{P}^1$ such that $\phi_2(0) = \phi_2(1) = \phi_2(d) = \infty$. Three roots of $f_3(x) = x^3 - ax^2 + bx - c$ go to 2-torsion points s_1, s_2, s_3 of E_2 and 0 is the fifth branch point of ϕ_2. Solving the corresponding system we get s_1, s_2, s_3 in terms of a and c. Then j_2 is

$$j(E_2) = -\frac{16}{C} \cdot \frac{B^3}{c\left((a-1)^2-4c\right)}$$

where A is as above and $B = a^4 - 2a^3 + a^2 - 24ca + 36c$.

5.2. Degenerate Cases

Notice that only one degenerate case can occur when $n = 3$. In this case, one of the Weierstrass points has ramification index 3, so the cover is totally ramified at this point, see theorem 3.1.

LEMMA 5.2: *Let E be an elliptic curve given by $y^2 = z(z-1)(z-s)$. Suppose that the genus two curve C with equation*

$$Y^2 = x(x-1)(x-w_1)(x-w_2)(x-w_3)$$

covers E, of degree 3, such that the covering is degenerate. Then w_3 is given by

$$w_3 = \frac{(4w_1^3 - 7w_1^2 + 4w_1 - w_2)^3\,(4w_1^3 - 3w_1^2 - w_2)}{16w_1^3(w_1-1)^3\,(4w_1^3 - 6w_1^2 + 3w_1 - w_2)}$$

and w_1 and w_2 satisfy the equation,

$$w_1^4 - 4w_1^3w_2 + 6w_1^2w_2 - 4w_1w_2 + w_2^2 = 0 \tag{2}$$

Moreover,

$$s = -27\left(w_1(w_1-1)\frac{(4w_1^3 - 7w_1^2 + 4w_1 - w_2)(4w_1^3 - 5w_1^2 + 2w_1 - w_2)}{(4w_1^3 - 9w_1^2 - w_2 + 6w_1)(4w_1^3 - 3w_1^2 - w_2)(4w_1^3 - 6w_1^2 + 3w_1 - w_2)}\right)^2$$

Proof: We take $\psi : C \to E$ and $\phi : \mathbb{P}^1 \to \mathbb{P}^1$ its corresponding Frey-Kani covering. To compute ϕ, let w_1 be the point of ramification index 3. Take a coordinate in the lower $\mathbb{P}^1$ such that $\phi(w_1) = 0$, $\phi(w_2) = s$, $\phi_2(w_3) = 1$, and $\phi(0) = \phi(1) = \phi(\infty) = \infty$. We denote points of ramification index 2 in the fibers of s and 1 by p and q, respectively. Then, ϕ is given as $z = k_2 \frac{(x-w_1)^3}{x(x-1)}$. From the corresponding system we get the above result. □

Denote the j-invariant of E by j_1. Using the above expression of s in terms of w_1 and w_2 we get an equation in terms of j_1, w_1, and w_2. Taking the resultant of this expression and equation (2) we get,

$$\begin{aligned}
&2617344w_1^2 + 38637j_1w_1^7 - 17496j_1w_1^6 - 29207808w_1^5 - 7569408w_1^3 - 7569408w_1^15 \\
&-729w_1^4j_1 + 5103j_1w_1^5 + 69984j_1w_1^9 - 60507j_1w_1^8 + 65536 - 589824w_1 + 16411392w_1^4 \\
&-29207808w_1^{13} + 44960208w_1^{12} - 60666336w_1^{11} + 72010800w_1^{10} + 44960208w_1^6 \\
&-60666336w_1^7 + 72010800w_1^8 - 75998272w_1^9 + 16411392w_1^{14} + 2617344w_1^{16} - 589824w_1^{17} \\
&-60507j_1w_1^{10} + 38637j_1w_1^{11} - 17496j_1w_1^{12} + 5103j_1w_1^{13} - 729j_1w_1^{14} + 65536w_1^{18} = 0
\end{aligned} \tag{3}$$

We denote with j the j-invariant of the elliptic curve $y^2 = (x-w_1)(x-w_2)(x-w_3)$. Then, proceeding as above, j can be expressed in terms of w_1 as below,

$$\begin{aligned}
&65536w_1^6 - 196608w_1^5 + 356352w_1^4 - 385024w_1^3 + (289536 - 9j)w_1^2 \\
&\qquad + (-129792 + 9j)w_1 + 35152 - 9j = 0
\end{aligned} \tag{4}$$

Taking the resultants of the two previous equations we have

$$256\, A(j)\, j_1^3 + 3\, B(j)\, j_1^2 + 6\, C(j)\, j_1 - D(j) = 0 \tag{5}$$

where

$$\begin{aligned}
A(j) &= (9j - 35152)^4 \\
B(j) &= -2187j^7 + 38996640j^6 - 277882258176j^5 + 998642127618048j^4 \\
&\quad - 1868045010870009856j^3 + 1669509508048367910912j^2 \\
&\quad - 543484034691057422696448j + 166124820572448211172518912 \\
C(j) &= 27j^8 + 1125216j^7 + 9650655872j^6 - 31593875152896j^5 + 27748804997283840j^4 \\
&\quad + 11145152843585106739 20j^3 - 6061989956030939246100480j^2 \\
&\quad + 834639785924776752461119 4880j + 3530196910060364873762938 55232 \\
D(j) &= (j^3 + 33120j^2 + 290490624j - 310747594752)^3
\end{aligned} \tag{6}$$

For the genus 2 curve C we compute the Igusa invariants J_2, J_4, J_6, J_{10} in terms of the coefficients of the curve, see Igusa (8) for their definitions. The absolute invariants of C are defined it terms of Igusa invariants as follows,

$$i_1 := 144\frac{J_4}{J_2^2}, \quad i_2 := -1728\frac{J_2J_4 - 3J_6}{J_2^3}, \quad i_3 := 486\frac{J_{10}}{J_2^5} \tag{7}$$

Two genus 2 curves with $J_2 \neq 0$ are isomorphic if and only if they have the same absolute

invariants. The absolute invariants can be expressed in terms of w_1 and w_2. Taking the resultant of the first two equations in (7) we get an equation $F(i_1, i_2, w_1) = 0$. The resultant of $F(i_1, i_2, w_1)$ and equation (4) we get $j = 13824 \frac{S}{T}$ where S and T are:

$$
\begin{aligned}
S &= 247945848003 i_1^3 - 409722141024 i_1^2 - 7591354214400 i_1 + 17736744960000 \\
&\quad + 61379512488 i_1 i_2 + 64268527400 i_1^2 i_2 - 2031496516224 i_2 \\
T &= 1034723291140 i_1^2 i_2 - 3175485076512 i_1 i_2 - 7250280129792 i_2 + 1670535171333 i_1^3 \\
&\quad + 366156782208 i_1^2 - 67382113075200 i_1 + 141893959680000
\end{aligned}
\tag{8}
$$

The conjugate solutions of (5) are j-invariants of E_1 and E_2. For $j = 0$ the equation (3) has one triple root $j_1 = -\frac{1213857792}{28561}$. Then, C and E are given by,

$$Y^2 = x^5 - x^4 + 216x^2 - 216x$$

$$y^2 = x^3 - 668644200x + 6788828143125$$

For $j = 1728$ the values for j_1 are

$$j_1 = 1728, \quad \frac{942344950464}{1500625}, \quad \frac{942344950464}{1500625}$$

This value of j does not give a genus 2 curve since the discriminant J_{10} of C is 0.

Next we will see what happens when both ϕ_1 and ϕ_2 are degenerate. We find only two triples (C, E_1, E_2) such that the corresponding $\phi_i : C \to E_i$, $i = 1, 2$, are degenerate. It is interesting that in both cases E_1 and E_2 are isomorphic.

LEMMA 5.3: *Let $E : y^2 = z(z-1)(z-t)$ be an elliptic curve. Then the genus 2 curve*

$$Y^2 = x(x-1)\left(x^3 - \frac{3}{2}x^2 + \frac{9}{16}x - \frac{t}{16}\right)$$

covers E, such that the covering is of degree 3 and the corresponding Frey-Kani covering of type II, iii) (Theorem 3.1), for $t \neq 0, 1$.

Proof: Let ϕ_1 be the Frey-Kani covering with $deg\,(\phi_1) = 3$ such that $\phi_1(w_1) = \phi_1(w_2) = \phi_1(w_3) = t$, $\phi_1(0) = 0$, $\phi_1(1) = 1$, $\phi_1(\infty) = \infty$. Let ∞ be the point of ramification index 3, and denote the points of ramification index 2 in the fibers of 0 and 1 with m and n respectively. If z is a coordinate in the lower $\mathbb{P}^1$ then ϕ_1 is given by $z = k_1 x(x-m)^2$. The relations $z - 1 = k_1(x-1)(x-n)^2$, $z - t = k_1(x^3 - ax^2 + bx - c)$ hold, where $x^3 - ax^2 + bx - c = (x-w_1)(x-w_2)(x-w_3)$. Comparing the coefficients and solving the system, we get

$$(a, b, c, k_1, m, n) = \left(\frac{3}{2}, \frac{9}{16}, \frac{t}{16}, 16, \frac{3}{4}, \frac{1}{4}\right)$$

$\square$

To compute ϕ_2, let w_1 be the point of ramification index 3. Take a coordinate in the lower $\mathbb{P}^1$ such that $\phi_2(w_1) = 0$, $\phi_2(w_2) = s$, $\phi_2(w_3) = 1$, and $\phi_2(0) = \phi_2(1) = \phi_2(\infty) = \infty$. The

points of ramification index 2 in the fibers of s and 1 we denote by p and q, respectively. Then ϕ_2 is given as $z_2 = k_2 \frac{(x-w_1)^3}{x(x-1)}$. Then from the corresponding system we get

$$\begin{aligned} w_1 &= -\frac{q(q-2)}{(2q-1)}, \; w_2 = \frac{-q^3(q-2)}{(2q-1)}, \; w_3 = \frac{-q(12q-8-6q^2+q^3)}{(2q-1)^3}, \\ k_2 &= \frac{1}{27}\frac{(-1+2q)^3}{q^2(q-1)^2}, \; s = \frac{-1}{27}\frac{(-1+2q)^2(q-2)(-3q+q^3-2)}{q^2(q-1)^2} \end{aligned} \tag{9}$$

Using the fact that the a, b, c are the symmetric polynomials of w_1, w_2, w_3 we have;

$$(t, q) = \left(\frac{1}{2}, \frac{1}{2} \pm \frac{1}{2}\sqrt{3}\right), \left(\frac{-241+22I\sqrt{2}}{2+22I\sqrt{2}}, \pm\frac{1}{2}I\sqrt{2}\right), \left(\frac{243}{2+22I\sqrt{2}}, 1 \pm \frac{1}{2}I\sqrt{2}\right) \tag{10}$$

where $I = \sqrt{-1}$. So we have three pairs of elliptic curves

$$E_1 : y^2 = z(z-1)(z-\frac{1}{2}) \quad and \quad E_2 : y^2 = z(z-1)(z+1)$$

with $j(E_1) = j(E_2) = 1728$.

$$E_1 : y^2 = z(z-1)\left(z - \frac{241+22I\sqrt{2}}{-2+22I\sqrt{2}}\right), \quad E_2 : y^2 = z(z-1)\left(z - \frac{241+22I\sqrt{2}}{243}\right)$$

with $j(E_1) = j(E_2) = \frac{-873722816}{59049}$.

$$E_1 : y^2 = z(z-1)\left(z - \frac{243}{1+2(11I\sqrt{2}}\right), \quad E_1 : y^2 = z(z-1)\left(z - \frac{241-22I\sqrt{2}}{243}\right)$$

and $j(E_1) = j(E_2) = \frac{-873722816}{59049}$. The last two cases correspond to the same isomorphism class of genus 2 curves. Thus, when ϕ_1 and ϕ_2 are both degenerate then we get two isomorphism classes of elliptic curves. Summarizing everything above we have the following table:

Table 1:

$f_3(x)$	E_1	E_2	$j_1 = j_2$
$x^3 - \frac{3}{2}x^2 + \frac{9}{16}x - \frac{1}{32}$	$z(z-1)(z-\frac{1}{2})$	$z(z-1)(z+1)$	1728
$x^3 - \frac{3}{2}x^2 + \frac{9}{16}x - \frac{241+22I\sqrt{2}}{-32(1+11I\sqrt{2})}$	$t_1 = \frac{241+22I\sqrt{2}}{-2+22I\sqrt{2}})$	$t_2 = \frac{241+22I\sqrt{2}}{243}$	$\frac{-873722816}{59049}$

where $C : Y^2 = x(x-1)f_3(x)$, $E_i : y^2 = z(z-1)(z-t_i)$. One can check, using the absolute invariants of the genus two curves, that they are not isomorphic to each other. Moreover, an equation for $E_1 \cong E_2$ in the second case is as follows:

$$y^2 = z^3 + z^2 - 277520614451197z + 1880509439898307064603$$

and its conductor $N = 2^8 \cdot 3 \cdot 11^2 \cdot 239^2 \cdot 251^2$.

5.3. Curves of genus 2 with degree 5 elliptic subfields, the 4-cycle case.

Notice that the case II, i) does not occur when $n = 5$. So we will consider only case II, iii). We will prove the following lemma:

LEMMA 5.4: *Let $\psi : C \to E_1$ be a covering of degree 5 such that the corresponding Frey-Kani cover is of ramification type II, iii) (theorem 3.1). Then the genus two curve can be given by*

$$Y^2 = x(x-1)(x-d)(x^3 - ux^2 + vx - w)$$

where

$$d = \frac{(3u^2 - 4u - 4v + 1)^2}{(2u-3)(6u^2 - 10u + 5 - 8v)}, \quad w = -\frac{(u^2 - 6u + 4v + 5)(u^2 - 4v)}{8(2u-3)}$$

and u and v satisfy

$$15u^4 - 82u^3 - 8vu^2 + 159u^2 - 140u + 56vu - 16v^2 - 52v + 50 = 0$$

Moreover, an equation of E_1 is $y^2 = z(z-1)(z-t)$, where

$$t = \frac{(u^2 - 4v)(-8u^4 + 24u^3 + 63u^2 + 64v^2 - 192uv + 196v + 16u^2v - 180u + 100)}{(2u-3)(6u^2 - 10u + 5 - 8v)}$$

Proof: Take the genus 2 curve to be

$$Y^2 = x(x-1)(x-d)(x^3 - ux^2 + v - w)$$

Let ϕ_1 be the Frey-Kani covering with $deg\,(\phi_1) = 5$ such that $\phi_1\,(w_1) = \phi_1\,(w_2) = \phi_1\,(w_3) = t$, $\phi_1\,(0) = 0$, $\phi_1\,(1) = 1$, and $\phi_1\,(d) = \infty$. Take ∞ to be the point of ramification index 4 such that $\phi_1\,(\infty) = \infty$. Then ϕ_1 is given by

$$z = k_1 \frac{x(x^2 - ax + b)^2}{(x-d)}$$

Solving the corresponding system we get the above result.

□

From the previous lemma, the j-invariant of the elliptic curve satisfies

$$F(u,v)j + G(u,v) = 0$$

Taking the resultant of the previous two equations, the j-invariant satisfies an equation of degree 2:

$$A(u)j^2 + B(u)j + C(u) = 0 \tag{11}$$

where

$$A(u) = (u-1)^2(u-2)^2(3u-4)^6(3u-5)^6(2u^2-6u+5)^8 \tag{12}$$

$$
\begin{aligned}
B(u) = &-16(-7105017544704u^{33} - 2816860828336128u^{31} + 175917390077952u^{32} + \\
&6231161224911759456285 20u^{12} + 165647363105986609 + 1071822623072391493632u^{24} \\
&- 6976649084949199627344 00u^{13} + 1016577017817153532825 6u^{22} - \\
&352117807701796262707 2u^{23} - 6113660399334195823564 80u^{15} + \\
&2110882088012752934471 68u^{18} - 1178433392388280162629 12u^{19} - \\
&3372587696055840670644 48u^{17} + 4807993966223918155993 60u^{16} + \\
&5861289860338751756966 4u^{2}0 + 139314069504u^{34} - 129094844198807347 20u^{27} - \\
&284837487810868721664u^{25} + 65530387559293083648u^{26} + 40376325064521521748u^{2} - \\
&28402917005791801887 6u^{3} - 3711757861451181852u - 57498283917355875893 64u^{5} + \\
&14521585643762721083 06u^{4} + 18345524820571264661416u^{6} - \\
&48457022965012856084616u^{7} + 108027612722856481764222u^{8} - \\
&206208961788595840640856u^{9} + 340743378168336968325408u^{10} - \\
&491546319356455960291344u^{11} - 25922857282984031345664u^{21} + \\
&692593865844403162989888u^{14} + 32784067604201472u^{30} + 2146611912787372032u^{28} \\
&- 295513372833693696u^{29})(2u^2 - 6u + 5)^4
\end{aligned}
\tag{13}
$$

$$
\begin{aligned}
C(u) = &\ 256(186624u^{16} - 4478976u^{15} + 50512896u^{14} - 355332096u^{13} + 1744993152u^{12} \\
&- 6343287552u^{11} + 17655393792u^{10} - 38378452608u^{9} + 65842249648u^{8} \\
&- 89441495616u^{7} + 95875417216u^{6} - 80237127456u^{5} + 51388251464u^{4} - 24345314544u^{3} \\
&+ 8044840448u^{2} - 1656421080u + 160064701)^3
\end{aligned}
$$

The solutions of (11) give the j-invariants of E_1 and its complement E_2.

EXAMPLE 5.1: *The two elliptic curves are isomorphic when the equation*

$$A(u)j^2 + B(u)j + C(u) = 0$$

of the above lemma has a double root. This happens for $u = \frac{3}{2} \pm \frac{1}{4}\sqrt{-5}$. *Then*

$$j_1 = j_2 = \frac{28849701763}{16941456}$$

The elliptic curve with j-invariant as above has equation,

$$y^2 + yz = z^3 + 6388018241406303862z - 7543791818526004449802921 08$$

5.4. Curves of genus 2 with degree 7 elliptic subfields, 4-cycle case

The case $n = 7$ is the first case that all degenerations occur. However, it is very difficult to compute the space of genus 2 curves with degree 7 elliptic subcovers. We discuss only one

degenerate case, namely case II. iii) of theorem 3.1. We will assume that the genus two curve is given by

$$C : Y^2 = x(x-1)(x-d)(x^3 - ax^2 + bx - c)$$

and the elliptic curve in Legendre form $E_1 : y^2 = z(z-1)(z-t)$. Moreover, let's assume that the corresponding Frey-Kani covering $\phi : \mathbb{P}^1 \to \mathbb{P}^1$ is of type II, i) of theorem 3.1. Take the coordinates such that, $\phi(0) = 0$, $\phi(1) = 1$, $\phi(d) = t$, and three distinct roots of $x^3 - ax^2 + bx - c$ are in the fiber of infinity. Let the point of ramification index 4 be infinity, which is in the same fiber as roots of $x^3 - ax^2 + bx - c$. Then the cover is given by,

$$z = k \frac{x\, P_1^2(x)}{x^3 - ax^2 + bx - c}$$

where $P_1(x)$ is a cubic polynomial which represents the three points of order 2 in the fiber of 0. Solving the corresponding system we get,

$$\begin{aligned}
a =& \frac{-1}{4A}(7d^{20} + 424t^4d^8 - 11072d^{12}t^3 + 2368t^3d^{13} - 872d^{16}t^2 - 1532d^{17}t - 21568d^{14}t^2 - 56d^{19}t \\
&+ 478d^{18}t + 36t^5d - 42t^5d^2 + 18160t^3d^{11} - 4356t^3d^{10} - 624t^4d^6 + 8t^5d^3 - 736t^4d^7 \\
&- 52594t^2d^{12} + 624td^{14} - 2576td^{15} + 2725td^{16} + 736td^{13} - 36d^{19} - 2368t^2d^7 + 42d^{18} \\
&+ 6112d^{15}t^2 - 29576t^3d^9 - 7t^5 + 52594t^3d^8 - 44496t^3d^7 + 2576t^4d^5 - 2725t^4d^4 \\
&+ 1532t^4d^3 + 56t^4d + 872t^3d^4 - 6112t^3d^5 - 478t^4d^2 - 18160d^9t^2 - 424d^{12}t + 11072d^8t^2 \\
&- 8d^{17} + 44496t^2d^{13} + 21568t^3d^6 + 4356d^{10}t^2 + 29576t^2d^{11}) \\
b =& \frac{1}{16A}(-14d^{21} + 77d^{20} + 400d^9t^4 - 3496t^4d^8 + 94280d^{12}t^3 + 1680t^3d^{14} - 21232t^3d^{13} \\
&+ 1008d^{17}t^2 + 35d^{17}t + 31612d^{14}t^2 + 84d^{20}t - 616d^{19}t + 1313d^{18}t - 77t^5d + 121t^5d^2 \\
&- 10356t^4d^6 - 72t^5d^3 + 9016t^4d^7 + 20t^5d^4 - 139344t^2d^{13} + 269886t^2d^{12} - 9016td^{14} \\
&- 5222td^{16} + 3496td^{13} - 121d^{19} - 1680t^2d^7 - 20d^{17} + 72d^{18} + 5352d^{15}t^2 - 269886t^3d^9 \\
&+ 139344t^3d^8 - 31612t^3d^7 + 5222t^4d^5 - 35t^4d^4 - 5352t^3d^6 - 1313t^4d^3 - 84t^4d - 1008t^3d^4 \\
&+ 616t^4d^2 - 94280d^9t^2 - 400d^{12}t + 21232d^8t^2 + 219712d^{10}t^2 - 308478t^2d^{11} + 308478t^3d^{10} \\
&- 219712t^3d^{11} + 5080t^3d^5 - 5080d^{16}t^2 + 10356td^{15} + 14t^5) \\
c =& -\frac{1}{448\,A}(28d^{11} - 7d^{12} - 561d^4t^2 - 1800d^7t + 84d^{10}t + 12t^2d + 364t^2d^3 - 118t^2d^2 + t^3 \\
&+ 20d^9 + 120td^4 - 608td^5 + 1400td^6 + 1311td^8 - 42d^{10} - 140d^6t^2 - 504d^9t + 440d^5t^2)^2
\end{aligned} \tag{14}$$

where,

$$\begin{aligned}
A =& d(90d^4t^2 - 36d^7t - 9t^2d - 84t^2d^3 + 36t^2d^2 + t^3 - d^9 + 36td^4 - 90td^5 + 84td^6 + 9td^8 \\
&- 36d^5t^2)\,(168td^6 - t^2 - 168td^5 - 20td^3 + 6t^2d - 10t^2d^2 + 5t^2d^3 + 90td^4 - 90d^7t + 20td^8 \\
&- 6d^{10} + d^{11} + 10d^9 - 5d^8)
\end{aligned} \tag{15}$$

Also, t and d satisfy the equation,

$$\begin{aligned}
&d^{16} - 16(td^{15} + t^3d) + 120td^{14} - 560td^{13} + (400t^2 + 1420t)d^{12} - (2400t^2 + 1968t)d^{11} \\
&+ (6608t^2 + 1400t)d^{10} - (11040t^2 + 400t)d^9 + 12870t^2d^8 - (400t^3 + 11040t^2)d^7 + 120t^3d^2 \\
&+ (1400t^3 + 6608t^2)d^6 - (1968t^3 + 2400t^2)d^5 + (1420t^3 + 400t^2)d^4 - 560t^3d^3 + t^4 = 0
\end{aligned} \tag{16}$$

Thus, we can express the coefficients of C in terms of t and d. Absolute invariants i_1, i_2, i_3 of C can be expressed in terms of t and d. Using resultants and a symbolic computational package as Maple we are able to get an equation in terms of i_1, i_2, i_3. The equation is quite large for display. This is the moduli space of genus two curves whose Jacobian is the product of two elliptic curves and the Frey-Kani coverings are of degree 7 and ramification as above.

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